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978-1-107-14538-2 — Planetary Geoscience
Harry Y. McSween, Jr , Jeffrey E. Moersch , Devon M. Burr , William M. Dunne , Joshua P. Emery , Linda C. Kah , Molly C. McCanta
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Planetary Geoscience

For many years, planetary science has been taught as part of the astronomy curriculum, from a very physics-based perspective, and from the framework of a tour of the Solar System – body by body. Over the past decades, however, spacecraft exploration and related laboratory research on extraterrestrial materials have given us a new understanding of planets and how they are shaped by geologic processes.

Based on a course taught at the University of Tennessee, Knoxville, this is the first textbook to focus on geologic processes, adopting a comparative approach that demonstrates the similarities and differences between planets, and the reasons for these. Profusely illustrated, and with a wealth of pedagogical features, this book provides an ideal capstone course for geoscience majors – bringing together aspects of mineralogy, petrology, geochemistry, volcanology, sedimentology, geomorphology, tectonics, geophysics, and remote sensing.

Harry Y. McSween, Jr. is Chancellor's Professor Emeritus of Planetary Geoscience at the University of Tennessee, Knoxville. He holds degrees from The Citadel (BS), the University of Georgia (MS), and Harvard University (PhD). His research focuses on meteorites and has resulted in the publication of hundreds of scientific papers on the subject. He has also authored three popular books on planetary science, as well as textbooks in geochemistry and cosmochemistry. He has served as co-investigator for many NASA spacecraft missions, including Mars Pathfinder, Mars Exploration Rovers, Mars Odyssey orbiter, and Dawn asteroid orbiter. McSween has been elected President of the Meteoritical Society and of the Geological Society of America, and is a fellow of the American Academy of Arts and Sciences. He is the recipient of the Leonard Medal (Meteoritical Society), the J. Lawrence Smith Medal (US National Academy of Sciences), and the Whipple Award (American Geophysical Union), and is the namesake for asteroid 5223 McSween.

Jeffrey E. Moersch is Professor of Planetary Science at the University of Tennessee, Knoxville. He holds degrees from Cornell University (BA, MS, and PhD) and Arizona State University (MS). His research focuses on remote sensing, planetary surface geology, instrument development, and terrestrial analog field work. He has served on the science teams for many NASA spacecraft missions, including the Mars Exploration Rovers, Mars Science Laboratory, and Mars Odyssey. Along with Professor McSween, he originally developed the planetary geology course from which this book is derived. Professor Moersch has authored and co-authored more than 80 peer-reviewed scientific articles and book chapters, and served for five years as the Mars editor for the scientific journal *Icarus*.

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Devon M. Burr is Associate Professor of Planetary Science at the University of Tennessee, Knoxville. She holds degrees from the United States Naval Academy (BS), St. John's College, Santa Fe (MA), University of Iowa (MS), and University of Arizona (PhD). Her research has focused on planetary geomorphology and she is currently conducting research on fluvial, aeolian (wind-driven), and tectonic landscapes and processes on planetary bodies, using image analysis and wind tunnel experiments (featured on the cover of *National Geographic* magazine for kids, entitled Dr. E's Super Stellar Solar System!). Burr is the lead editor of the book *Megaflooding on Earth and Mars* (Cambridge University Press, 2009). She is also a member of the Geological Society of America (and former member of the GSA Planetary Geology Division management board), the AAS Division of Planetary Sciences (serving as Science Organizing Committee Chair for DPS 2018), the American Geophysical Union, and the namesake of asteroid DevonBurr.

William M. Dunne is Professor of Geology at the University of Tennessee, Knoxville. He received his BS and PhD in geology from the University of Bristol, England. His research concerns the development of mountain belts and characterization of fracture networks in rocks. The latter interest has practical importance with regard to hydrocarbon exploration and groundwater remediation efforts, leading to collaborations with civil engineers. Dunne serves as an editor of the *Journal of Structural Geology*, is a fellow of the Geological Society of America, and has served as chair of the GSA Structural Geology and Tectonics Division and the ASEE Engineering Research Council. He has received teaching awards from the department, college and university.

Joshua P. Emery is the Lawrence A. Taylor Associate Professor of Planetary Science at the University of Tennessee, Knoxville. He received his BS from Boston University and PhD from the University of Arizona. His research focuses on investigating the formation and evolution of the Solar System and the distribution of organic material. As an observational planetary astronomer, he applies the techniques of reflection and emission spectroscopy of primitive and icy bodies in the near- (0.8–5.0 micron) and mid-infrared (5–50 micron). Current projects include the Jupiter Trojan asteroids, Kuiper Belt objects, icy satellites, and other asteroids. He is leader of the Thermal Analysis Working Group on the OSIRIS-REx asteroid sample return mission and the Surface Composition Working Group on the Lucy Trojan asteroid flyby mission.

Linda C. Kah is Professor of Carbonate Sedimentology and Geochemistry at the University of Tennessee, Knoxville. She received concurrent BS and MS degrees in geology from MIT, followed by a PhD from Harvard. Her research integrates sedimentology, stratigraphy, geochemistry, and paleobiology to understand the evolution of the Earth's biosphere. Current projects include reconstructing the ocean–atmospheric oxygenation and the redox structure of Mesoproterozoic shallow marine systems, exploring the effects of changing ocean circulation on the Great Ordovician Biodiversification Event (GOBE), and characterizing microbe–mineral interactions in the mineralization of Holocene lacustrine microbialites. In addition to Earth-based research projects, she also investigates potential habitable environments as co-investigator on the Mars Science Laboratory Mission.

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Molly C. McCanta is Associate Professor of Mineralogy and Petrology at the University of Tennessee, Knoxville. She received her BS from the University of Oregon and concurrent MSc and PhD from Brown University. Her research focuses on the record of igneous processes retained in mineral grains as a means of better understanding geologic processes in planetary interiors. Current projects include experimentally investigating mineral and melt redox conditions as a function of planetary evolution, constraining the timing of eruptive hazards at several Costa Rican volcanoes, determining weathering geochemistry on the surface of Venus, and identifying cryptotephra layers in deep sea drill cores.

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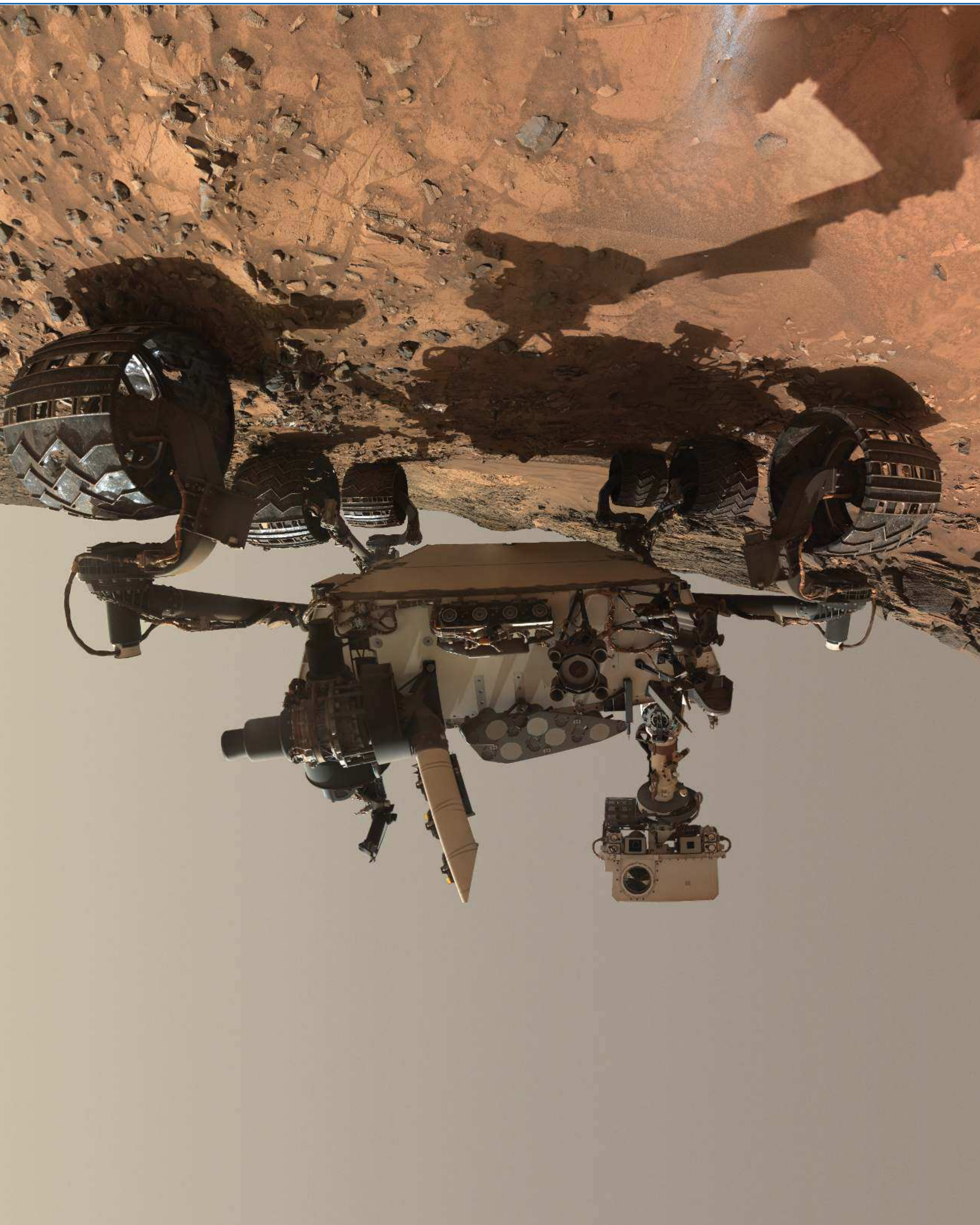

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Preface: Geologic Processes in the Solar System

> When we explore other worlds, what once seemed the only way a planet could be turns out to be somewhere in the middle range of a vast spectrum of possibilities. . .
>
> *Carl Sagan, 1995,* Pale Blue Dot: A Vision of the Human Future in Space

> When one world is not enough.
>
> *Motto of the Geological Society of America's Planetary Geology Division*

Planet Earth has always been the geoscientist's laboratory. Now, though, after decades of planetary exploration, geoscientists recognize that our own world is but a singular grand experiment, and that other planets afford opportunities to examine nature's geologic experiments run with different starting compositions and under varying conditions. What used to be considered a part of astronomy now rightly belongs to geology. This substantial shift of scientific real estate has greatly expanded geology's reach, as distant points of light have been transformed into worlds shaped by more-or-less familiar geologic processes.

This book focuses on geologic processes on the planets, moons, and smaller bodies (asteroids, comets) of the Solar System. These processes are revealed and understood through exploration by orbiting or flyby spacecraft, landers and rovers, and, in the case of the Moon, by astronauts. Much of planetary geoscience involves remote sensing – visible observations, as well as measurements that use other parts of the electromagnetic spectrum ranging from gamma rays to radio waves. The application of geochemical and geophysical methods and numerical models also play significant roles. And, as in terrestrial geology, extraterrestrial samples analyzed in the laboratory constrain and quantify planetary geologic processes.

The book begins with a Grand Tour, an overview of the geologic bodies in the Solar System. Rather than taking the traditional approach of stepping outward planet by planet, we consider the temporal history of Solar System exploration in the spacecraft era and the critical role that has been played by geoscience.

Of necessity, planetary geoscientists often employ different tools than those used by geologists on Earth. Some of these will be familiar to geology students, but with different twists.

- Imaging and spectroscopy: The principles of visible/ultraviolet, near-infrared/ thermal infrared, X-ray, gamma ray, neutron, and radio spectroscopy are introduced, focusing on what kinds of data are provided by remote-sensing measurements at various wavelengths and how they are interpreted.
- Geochronology: The application of stratigraphic principles and crater density measurements provide the means of determining the relative ages of planetary surfaces, supplemented by radiometric dating of samples, where available, for absolute age determinations.
- Geologic mapping: We will see how spacecraft images are obtained and used to identify and map stratigraphic, structural, and geomorphic features, and how geologic mapping techniques at different spatial scales are complemented by remote sensing data.
- Geophysical methods: Topography, gravity, magnetics, and seismic data, as well as density and moment of inertia, are used to probe the unseen interiors of planets, along with numerical simulations and thermal evolution models.
- Laboratory analysis of planetary materials: Various kinds of directly sampled extraterrestrial materials are available for petrologic and geochemical analyses in the laboratory, and the laboratory has now been carried into the field by landed spacecraft.

Following chapters on the toolkits used by planetary geoscientists, the bulk of the book focuses on processes, which are introduced wherever possible through first principles. Each chapter begins with an overview and ends with a set of questions intended to provide the student with an opportunity to review important concepts and integrate what they have learned into a broad understanding of planetary geoscience. The subject matter follows this structure:

- Cosmochemical processes explain the origin of elements and isotopes as the building blocks of planets and how they were processed and fractionated in the early solar nebula.

- Observations and models help us understand the process of planetary accretion, as well as early collisional processes and orbital evolution.
- To understand planetary thermal evolution, we consider available heat sources and the resulting processes of melting and global differentiation.
- Modeling of planetary interiors requires an understanding of minerals stable at high pressures and temperatures, and how these phases are distributed.
- Planetary geodynamic processes are driven by gravity, heat flow, fluid mechanics, and rheology.
- Planetary tectonic processes differ on bodies with active versus stagnant lids.
- Igneous processes everywhere include magma generation, emplacement, and crystallization, but compositional and tectonic differences among planets yield varying results.
- Impact cratering is not a familiar process, so we consider crater mechanics, explore the geology of craters, and describe shock metamorphism.
- Some planets and many smaller bodies have volatiles sequestered in atmospheres, oceans (often subsurface), and ices.
- Wind-driven processes on bodies with atmospheres produce distinctive erosional and depositional landforms.
- The surfaces of some planets have been shaped by flowing and ponded water and other liquids.
- Physical and chemical weathering produce surficial regoliths and sedimentary deposits; aqueous alteration and thermal metamorphism affect rocks in the interiors of planets and asteroids; and mass wasting modifies planetary surfaces.
- For the emerging field of astrobiology, we review biological requirements and planetary habitability, and consider how life might be detected and how it influences a planet's evolution.
- A case study illustrates how all these kinds of information can be integrated into an understanding of the geologic processes that have shaped the evolution of a planet, in this case Mars.
- We end with an epilogue briefly exploring the diversity of exoplanets recently discovered around other stars, speculating about geologic processes on them.

The intended audience for this book is the undergraduate geology major, who already has had some exposure to mineralogy and petrology, sedimentology and stratigraphy, structure and tectonics, geochemistry, and geophysics. We provide limited background in these subjects as we go along, but some prior geologic coursework is assumed. For a decade, we have taught this course to geology majors at the University of Tennessee, and this experience has shaped our views of how to present this subject. However, we have been frustrated that a textbook focused on geoscience has not been available. Our goal is to help promote the integration of planetary geoscience into the undergraduate geology curriculum, by exploring the generality of geologic processes on other bodies. Although only a modest number of professional geologists actually work in planetary geoscience, ongoing planetary exploration has proved to be a powerful means of motivating the next generation of scientists and engineers.

We hope you will enjoy and learn from this foray into planetary geoscience, and come to appreciate that, although some of the tools may differ, the tried-and-true methods of geology work on other worlds too.

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